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⑯ Slotless electric motor or transducer and method for making same.

⑯ A slotless stator for an electromechanical transducer, said stator including a stator shell (30) and a pre-formed, at least partially rigid, self-supporting winding structure having active segments and endturns (40), is produced by a method that comprises depositing insulated wire on a support, adhesively affixing at least active wire segments portions to the support surface or previously deposited wires, with the active wire segments arranged in predetermined, substantially fixed positions with respect to each other, encapsulating and securely attaching the winding structure to the stator shell, and combining the completed stator with a structure including at least one permanent magnet mounted for movement relative to the stator. In a preferred embodiment, the self-supporting winding structure is removed from the support surface prior to insertion in the stator shell.

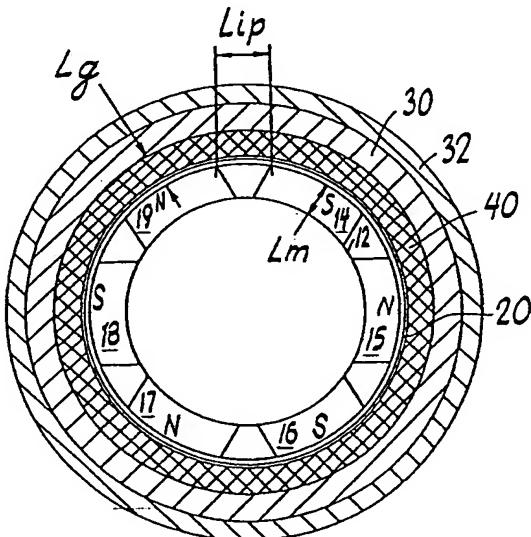


FIG. 1

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## BACKGROUND OF THE INVENTION

In the past, most electric motors were constructed according to slotted designs in which the copper conductors of the motor winding were placed between teeth in slots of the laminated iron rotor or stator structure. The slotted designs provide a motor with a relatively small air gap to achieve a desired high permeance. The recent advent of high energy permanent NdFeB (neodymium iron, boron) magnets has made slotless designs feasible in all motors, particularly in high performance servo motors. See, for example, US-A-4,954,739. In the slotless designs the copper windings are located in the air gap rather than in the slots.

Slotless motor designs have great potential advantages over conventional slotted designs. The slotless designs have a higher potential level of efficiency due to extremely low eddy current losses, extremely low hysteresis losses, the absence of cogging losses and the lack of appreciable iron losses. High speeds in the range of 40k to 120k rpm are readily attainable. The operation can be perfectly smooth over a wide speed range since there is no cogging due to the absence of teeth in the slotless design. Furthermore, the lack of magneto-strictive noise from the teeth of a normal design allows for very quiet operation. The slotless design is also capable of a faster motor response (acceleration/deceleration) due to a low inductance.

Various methods have been proposed for making the slotless motors. For example, in the aforementioned US-A-4,954,739 the winding is formed using a cylindrical support with a reduced diameter portion at one end. A fiberglass sleeve is placed around the uniform diameter portion and thereafter preformed coils are placed in position. When the coils are in place, the thicker end turn portions at one end of the winding are flared inwardly at the reduced diameter portion of the support and the other end of the winding is flared outwardly. The winding can then be inserted into the cylindrical back iron shell starting with the inwardly flared end of the winding. The support can thereafter be withdrawn from the outwardly flared end leaving the fiberglass sleeve as part of the motor structure. The winding is encapsulated using a suitable resin after the winding is inserted into the stator shell.

US-A-4,130,769 describes a layered preformed winding technique for making slotless, brushless DC motors. A fixture is utilized for preforming flat single layered coils. The preformed coils are placed in the back iron cylinder in a shingle layered fashion with one of the straight coil portions in an outer layer against the back iron and the other straight coil portion in an inner layer. This design

appears to be limited to windings with a two conductor thickness.

US-A-4,445,061 describes a method of making and utilizing a fixture which attaches to a cylindrical stator housing, having a smooth circumference wall. Once the stator is placed in the fixture, temporary fingers are extended radially inwardly. The coils are then wound around the fingers which form temporary slots similar to those in slotted motor designs. The conductors are thereafter forced outwardly against the inner wall of the back iron cylinder by a non-magnetic, expandable, reformable plastic cylinder.

US-A-4,645,961 describes the use of a long flexible printed circuit board insulated on both sides. The printed circuit board is rolled in "jelly roll fashion" and placed in the stator back iron cylinder. The winding is closed by soldering in connecting wires are appropriate locations.

In order to fully take advantage of the slotless motor design characteristics the active conductor portion of the winding in the air gap must be straight and parallel to each other and, preferably, to the motor axis of rotation. Any deviation from the parallel alignment decreases the rotatory torque produced by the current flow through the conductor and, hence, reduces efficiency of the motor. Furthermore, failure to achieve parallel alignment of the conductors results in a larger necessary air gap and a reduced thermal conductivity for removing heat from the winding. As a result of one or more of the factors, the past motor designs and methods of production have not been able to achieve the full potential of the slotless design at a reasonable cost.

## SUMMARY OF THE INVENTION

An object of the invention is to provide a slotless design for a transducer, such as an electric motor, and methods for making the same, in which the active conductor segments of the winding are straight and parallel to each other and, in the preferred embodiment, parallel to the axis of rotation throughout the length of the air gap. In the case of a linear motor, the active conductor segments of the winding are preferably parallel to one another and perpendicular to the direction of movement.

Another object of this invention is to provide a slotless design for a transducer, such as an electric motor, with a high copper packing density to minimize the necessary air gap to accommodate the winding or maximize the number of active conductor segments for a given air gap.

Still another object of the invention is to provide a slotless design for a transducer with good thermal conductivity for efficiently removing heat

from the winding.

Yet another object of the invention is to provide an efficient method for manufacture of a transducer or slotless motor.

In accordance with the present invention, the method for the manufacture of a slotless stator for an electromechanical transducer including a pre-formed, at least partially rigid, self-supporting winding structure having active segments and end-turn segments, comprises the steps of depositing insulated wire on a support surface; adhesively affixing at least active wire segment portions of said insulated wire to said support surface or previously deposited wires, with at least active wire segments of said winding structure attached in predetermined, substantially fixed positions with respect to other active segments of said winding structure; encapsulating and securely attaching said winding structure to the metal structure of the slotless stator; and combining the completed stator with one or more permanent magnet structures mounted for movement relative to said stator.

A preferred embodiment of this invention is directed to a method for the manufacture of a rotating electromechanical transducer including a slotless stator with a pre-formed, at least partially rigid winding structure inside a stator shell and a rotor provided with one or more permanent magnet(s), said method comprising the steps of (1) placing insulated wire on a cylindrical support surface, either said wire or said surface, or both, being coated or provided with an adhesive layer that can be activated by application of energy; (a) part of said insulated wire being dispensed parallel to the axis of said cylindrical support surface while travelling towards one end of said support surface to form an active conductor segment of said winding structure; (b) part of said insulated wire being dispensed to form a wire loop constituting an end-turn; (c) part of said insulated wire being thereafter dispensed while travelling in the reverse direction parallel to said axis to form another active conductor segment of said winding structure; (d) part of said insulated wire being next dispensed to form another wire loop constituting an end-turn; (e) repeating steps (a) to (d) until all winding coils of said winding structure are completed; (2) substantially simultaneously with dispensing at least part of said insulated wire, adhesively attaching at least portions of each active conductor segment on a continuous basis to form a cylindrical winding structure with at least the active conductor portions being adhered; (3) encapsulating said winding structure with a resinous composition while simultaneously adhesively bonding said winding structure of the stator shell; (4) disposing a rotor with at least one permanent magnet within said winding structure and completing the assembly of the electromechanical transducer.

Another preferred method comprises the steps of (1) dispensing and depositing insulated wire with wire scribing means on a cylindrical support surface, either said insulated wire or said cylindrical surface, or both, being provided with an adhesive layer that can be activated by application of energy; (a) part of said insulated wire being dispensed parallel to the axis of said cylindrical support surface while travelling towards one end of said support surface to form an active conductor segment of said winding structure; (b) part of said insulated wire being dispensed to form a wire loop constituting an end-turn; (c) part of said insulated wire being thereafter dispensed while travelling in the reverse direction parallel to said axis to form another active conductor segment of said winding structure; (d) part of said insulated wire being next dispensed to form another wire loop constituting an end-turn; (e) repeating steps (a) to (d) until all winding coils of said winding structure are completed; (2) substantially simultaneously with dispensing at least part of said insulated wire, adhesively attaching at least portions of each active conductor segment on a continuous basis to form a cylindrical winding structure with at least the active conductor portions being adhered; (3) encapsulating said winding structure with a resinous composition while simultaneously adhesively bonding said winding structure of the stator shell; (4) disposing a rotor with at least one permanent magnet within said winding structure and completing the assembly of the electromechanical transducer.

For rotary transducers or motors, insulated copper wire is deposited on a mandrel according to the desired winding configuration. Preferably, a removable sleeve or film wrap surrounds the mandrel and the winding is deposited thereon. While being deposited, the wire is adhered at the desired locations, at least in portions of the active straight air gap segments. The wire may be adhered on an ongoing continuous basis, or an intermittent basis, or may be adhered in sections where the active winding segments are located as a separate step after section of wire have been deposited. Preferably, the wire is adhered through the use of a heat activated adhesive either coated on the wire, or placed on the cylindrical surface, or both. Adhesive film may also be used by placing the adhesive film on the cylindrical surface or between layers. Heat activation is preferably achieved through the use of ultrasonic energy, but other energy sources can be used. The winding formed on the mandrel is a rigid or semi-rigid structure that can be removed from the mandrel and positioned in the back iron cylinder of the motor stator.

The method of this invention for linear motors is similar except that the winding structure is nor-

mally formed on a flat surface and the wire is deposited by controlling movement of a scribing head in two dimensions on the flat surface. With the linear motor, the active straight air gap segments of the winding are perpendicular to the direction of movement.

Once the formed winding structure is located relative the stator structure it must be rigidly affixed to the back iron. This is preferably achieved using wire coated with a two-stage adhesive or by using a two-stage adhesive film on the support surface or between conductor layers. In the normal state at room temperature the adhesive must be in a non-tacky state so as to not hinder despooling and feeding. While depositing the wire on the mandrel or support surface, the two-stage adhesive is heated sufficiently to tack the wire in place to form the rigid or semirigid winding structure. Thereafter, when the preformed winding is in place in the stator structure, the assembly is placed relative to an oven to cure or thermoset the adhesive resin so that the winding is rigidly adhered to the back iron. In some cases, a two-stage adhesive may be used with an encapsulant and both cured at the same time. Alternatively, if a two-stage resin is not used in forming the winding, a separate encapsulating resin can be injected and then cured to adhere the winding in place. The resin can be a composition filled with finely divided particles of soft iron or other magnetic material to improve the thermal and magnetic properties of the motor. As another alternative, an adhesive coated wire made of soft magnetic material can be wound around the winding structure to provide the back iron. The soft magnetic wire adhesive can be cured at the same time as the copper winding structure.

The apparatus for forming a winding according to one embodiment preferably includes a wire scribing head with at least two, and preferably three, degrees of control. The rotary position of the mandrel and the longitudinal position of the scribing head are controlled so that wire can be deposited according to the desired pattern on the cylindrical surface of the mandrel. The third degree of control is desired for multilayered windings where it is often necessary to control the height of the scribing head above the mandrel surface to accommodate the previously deposited layers. The three degrees of control are preferably achieved through a software computer program designed for the desired winding configuration and motor size. Similar apparatus can be used to form a winding for a linear motor where the scribing head is controlled to deposit the wire on a flat surface.

An alternate apparatus for forming the winding aligns the adhesive coated, insulated wire under tension so that the wire is parallel to the axis of rotation for the length of the air gap. Energy, pref-

erably ultrasonic, is applied to the straight wire segment or portions thereof to activate the adhesive. The straight conductor segment is pressed into contact with the mandrel surface or previously deposited segments. When the energy is removed, the wire segment forms part of the rigid or semi-rigid winding structure being formed.

#### GENERAL DESCRIPTION OF THE DRAWINGS

5 The foregoing and other objects of the invention will become obvious from the following detailed specification which incorporates the drawings.

10 Fig. 1 is a cross-sectional end view of the motor according to the invention.

15 Figs. 2A and 2B are a side view and an end view, respectively, of the rotor portion of the motor.

20 Fig. 3 is a cross-sectional view of the stator of the motor.

25 Fig. 4 is a schematic illustration showing the wire scribed head and associated apparatus for making a self-supporting winding structure according to the invention.

30 Fig. 5A is a cross-sectional diagram showing the wire scribing stylus for a single conductor and Fig. 5B is a cross-sectional drawing illustrating modifications of the ultrasonic stylus for three conductors.

35 Fig. 6 is a schematic illustration of the apparatus employing three scrolling heads to create a three phase winding structure.

40 Fig. 7 is an illustration of a tapered mandrel for use with the apparatus illustrated in Fig. 4.

45 Fig. 8 is an illustration of a tapered "drug cup" mandrel for use with the apparatus shown in Fig. 4.

50 Fig. 9 is a perspective illustration of an alternate apparatus for creating a winding structure wherein an entire active winding segment can be adhered at the same time.

55 Fig. 10 is a partially perspective and partially schematic illustration of an ultrasonic transducer and associated equipment for use in the apparatus of Fig. 9.

Fig. 11 is a cross-sectional view of the ultrasonic horn shown when capturing an insulated conductor.

Fig. 12 is a perspective view of an alternative embodiment wherein the ultrasonic horn is designed for a stitch type adherence of the insulated wire.

Fig. 13 is a perspective view of another alternative embodiment wherein the ultrasonic horn is narrow and movable relative to the mandrel to similarly achieve a stitch type adhesive.

Fig. 14 is a perspective schematic view of the stator of a linear motor made in accordance with the invention.

Fig. 15 is an illustration showing the moving permanent magnet in combination of the stator winding of the linear motor.

be used by the copper of the windings. If desired, small notches can be randomly located in the internal circumference of the laminations for better bonding to the winding against torque forces produced in the motor.

Apparatus according to one embodiment for creating the winding on a mandrel for subsequent insertion into the motor is illustrated in Fig. 4. The movement of a wire scribing head 50 is controlled relative to the surface of a mandrel 52 to dispense insulated, adhesive coated wire according to the desired winding pattern 51. The rotary position of the mandrel is controlled by an R drive 58. The longitudinal position of the wire scribing head 50 relative to the mandrel is controlled by an L drive 56. The height of the wire scribing head 50 relative to the surface of the mandrel according to the number of previously deposited winding layers is controlled by a Z drive 54. Drives 54 and 56 can be of the stepping motor driven lead screw type, as shown, or can be of the linear positioning type. A head direction control 60 controls the rotary position of the wire scribing head about the vertical axis so that the wire is dispensed in a direction according to the direction of movement relative to the mandrel surface. Drives 54, 56 and 58 are mounted on a frame 62 which, in turn, is mounted on a high mass base such as a large block of granite.

The mandrel is preferably wrapped with Kapton film coated on its outer side with an adhesive coating similar to that coated on the wire. The Kapton wrap must be used to facilitate removal of the winding.

The insulated wire used to form the winding is dispensed from a spool 66 mounted above frame 62. As will be explained hereinafter in more detail, the insulated wire is coated with an adhesive composition, preferably a two-stage adhesive which at moderate temperatures can tack the wire and subsequently quickly reverts to a non-tacky state, and at elevated temperatures is cured to its thermoset condition to form a rigid winding solidly secured to the stator structure. In the preferred embodiment, the winding structure is inserted into the stator shell, provided with an encapsulant and exposed to a temperature sufficient to cure the encapsulant and the adhesive wire coating.

The wire from the spool passes around a drive roller 68 which feeds the wire at the correct speed according to the movement of the scribing head 50 relative to the mandrel 52. Four idler rollers 70 press against the feed roller to maintain a friction grip on the wire. An ultrasonic stylus 72 straddles the wire at the point of contact with the mandrel surface. The stylus provides sufficient energy to heat the wire coating to the tacky state sufficient to adhere the wire to the mandrel surface. A suitable

## DETAILED DESCRIPTION OF THE INVENTION

The general structure of the motor made by the method and apparatus of the invention is shown in Figures 1 to 3.

The motor includes a steel shaft 10 surrounded by a cylindrical back iron sleeve 12. Six permanent magnets 14-19 are mounted on sleeve 12 extending radially and are magnetized to provide alternating north and south poles as shown in Fig. 1. In the preferred embodiment, the magnets are high energy product magnets with energy products in excess of 26 MGOs (MegaGauss Oersteds) and preferably in excess of 30 MGOs. Suitable permanent magnets are, for example, those made from neodymium, iron and boron which are available under the trade name NEOMAX-30H. The magnets are pressed, arcuate shaped magnets and are mounted on the back iron sleeve 12 surrounding shaft 10. Alternatively, one or more ring magnets could be used instead of the separate arcuate shaped magnets.

A banding 20 surrounds the rotor structure to hold the magnets in place under high speed centrifugal force conditions. Banding is accomplished using high strength Kevlar filaments which are dipped in epoxy and then wound around the rotor including one or more helical layers followed by several hoop layers.

The rotor can be constructed using six magnets each extending the full length of the rotor, or the magnets can be segmented as shown in Fig. 2A. An advantage of the segmented magnets is that a single motor design can produce motors of different horsepower ratings by simply changing the motor length and the number of magnet segments.

The stator structure includes a cylindrical outer shell 30 of laminated silicon steel which provides the outer ack iron for the motor. The laminations are assembled and then cast in an aluminum outer housing 32. The winding structure 40 is formed including straight active segments parallel to the axis of rotation and end turn segments. The winding structure 40, once formed, is then mounted inside the cylindrical back iron shell. The stator structure is slotless and, hence, the windings are located in the motor air gap between the permanent magnets of the rotor and the cylindrical inner surface of the stator shell. Since there are no teeth in the stator, the entire inner cylindrical surface can

wire scribing head structure is described in greater detail in US-A-4,641,773. A suitable adhesive coated insulated wire is available under the trade name "Bond M Wire" from Essex Corp.

A suitable two-stage adhesive for coating wire for use with this invention is described in US-A-4,642,321. The adhesive composition includes (a) a polymeric resin such as a polyester resin, a polyurethane resin or an epoxy resin, (b) a filler and (c) a curing agent which is capable of forming cross-links to cure the polymer resin but which is non-reactive blocked at the conditions that activate the adhesive composition. It is important that the adhesive composition be non-tacky at room temperature so that the coated wire can readily be unreeled from the spool and passed through the wire scribing head. The adhesive is activated by ultrasonic energy from the stylus as the wire is deposited and rapidly returns to the hardened state as the adhesive cools. The adhesive composition is also thermosetting so that it can be cured by heating to elevated temperatures well above the temperatures that activate the adhesive.

The winding can follow virtually any desired pattern. Fig. 4 shows the first coil 51 of a winding suitable for a six pole motor. The coil is in the form of a longitudinal spiral beginning at the center and extending until it covers about one third of the mandrel surface. Two similar additional coils can be formed so that a single layer winding covers the surface of the mandrel. Additional layers of the winding can then be formed on top of prior layers. Of particular importance is that the active conductor portions which will lie in the air gap of the completed motor between the end turn segments are formed straight and parallel to the axis of rotation. Such parallel conductors provide the most efficient energy to torque conversion, permit a high copper packing density and provide improved thermal dissipation by minimizing the potting material required to secure the winding. Using the method and apparatus of the invention permits formation of a winding with straight, parallel conductors in a substantially rigid self-supporting form prior to insertion into the stator structure and prior to curing of the resin.

The winding apparatus in Fig. 4 is preferably software controlled through a suitable computer. The computer is interfaced to control the rotary position of the mandrel through R drive 58, to control the longitudinal position of the scribing head relative to the mandrel through L drive 56, to control the height of the scribing head above the mandrel surface according to previously deposited wire layers via Z drive 54, to control the head direction through control 60 and to control drive roller 68 to dispense wire at the appropriate rate. Through the software control, the system can be

completely flexible since different types or sizes of windings can easily be made in any desired reproduction run by simply changing the software and possibly the mandrel size.

Figures 5A and 5B are cross-sectional views showing alternate embodiments for the ultrasonic stylus of the scribing head. Fig. 5A illustrates a stylus tip for a single conductor 81. The stylus tip partially surrounds the conductor and imparts ultrasonic energy to activate the adhesive surrounding the conductor to adhere the conductor. In the alternative embodiment illustrated in Fig. 5B, the ultrasonic stylus 84 is configured to partially surround three conductors 85-87 being deposited at the same time.

Fig. 6 illustrates an alternate embodiment for creating a three-phase winding using three scribing head active at the same time. The scribing heads 91, 92, 93 are displaced by 120 degrees from one another about the mandrel 90. The scribing heads 91-93 receive wire from separate spools 94, 95, 96, respectively. With this arrangement, three coils of a three-phase winding are formed simultaneously.

Figure 7 illustrates a winding apparatus with a tapered mandrel. As shown, the mandrel, dimensioned for a particular motor, has a diameter of 37.85 mm (1.49 in) at one end and a diameter of 36.78 mm (1.448 in) at the other end. The taper in the mandrel facilitates removal of the winding structure after formation.

Fig. 8 illustrates a tapered mandrel for forming a "drug-up" winding structure. This mandrel is tapered as is the case with the mandrel in Fig. 7 to facilitate removal of the winding structure. The smaller end of the mandrel has a reduced diameter section to accommodate end turns forming the bottom of the "cup".

Alternate apparatus for making a self supporting winding structure according to the invention is illustrated in Figures 9 to 11. In this embodiment, the adhesive coated, insulated wire is adhered a section at a time rather than on a continuous ongoing basis. The wire is aligned parallel to the axis of rotation, placed under tension and then pressed into the underlying surface while energy is applied to activate the adhesive. Thus, an entire active segment, or a portion thereof, is adhered at the same time.

The mandrel 100 (Fig. 9) includes an increased diameter portion 101 which corresponds in diameter to the diameter of the rotor in the motor being built. The length of the increased diameter portion corresponds to the active winding portion in the air gap of the motor. The end portions 102 and 103 of the mandrel have a reduced diameter to accommodate the winding end turns. A rotary position drive 105 is used to position the mandrel at an accuracy within arc minutes.

The increased diameter portion of the mandrel is wrapped with a Mylar film to facilitate easy removal of the winding structure after formation. The film is coated with a suitable thermoplastic material such as Kapton.

A pair of guide pins 107 and 108 is used to position the insulated wire 110 being dispensed from a suitable wire dispensing bobbin 112. As shown in Fig. 9, one end of the wire is secured so that the other end at bobbin 112 can place the straight wire section 110 under tension parallel to the axis of rotation.

Ultrasonic energy is provided to activate the adhesive on the mandrel surface or on the coated conductors. As shown in Fig. 10, an amplifier 114 is connected to a driving coil 116 surrounding an ultrasonic transducer 117. A microphone 120 picks up the vibration frequency of the transducer and is used to provide a feedback signal which maintains oscillation at the resonant frequency of the transducer. The microphone is coupled to a feedback control circuit 119 which determines both the frequency and amplitude of the drive signal supplied to the driving coil by amplifier 114.

Transducer 117 is coupled to a horn 122 which is shaped to provide a V-shaped groove parallel to the axis of rotation. The groove is dimensioned as shown in Fig. 11 such that between one-quarter and one-half the diameter of the insulated conductor 126 lies above the plane passing through the lower horizontal surface of the horn.

In the raised portion, as shown in Fig. 9, the V-shaped groove is located about 6.35 mm (0.25 in) above the surface below. When the ultrasonic horn moves downward, the wire 110 is captured in the V-shaped groove and urged downward toward the mandrel surface. The amount of ultrasonic energy supplied is determined empirically and is sufficient to heat the adhesive to the active state. The downward force is controlled to bring the wire into contact with the mandrel surface or the previously deposited wire such that the ultrasonic energy activates the contact surfaces. The downward force of the horn should not be sufficient to move any previously deposited conductors or disturb the layer integrity. The ultrasonic energy is removed about one-third of a second before raising the horn so that the adhesive can set before the V-shaped groove rises.

After a straight wire section is adhered, guide pins 107 and 108 are temporarily removed. The mandrel is rotated as wire is dispensed to form an end turn. The guide pins are then reset, and the bobbin 112 continues to dispense wire for the next active conductor run. Alternatively, this straight run section is placed under tension and then adhered by applying ultrasonic energy and pressing the conductor into the contact surface below. The

winding structure is formed by continuing in this fashion alternately forming straight conductor runs and end turns. At least the straight active conductor runs, or portions thereof, are adhered before going on to the next end turn or active conductor run.

The ultrasonic horn 122, Fig. 9, adheres the entire straight, active conductor run in a single operation.

Fig. 12 illustrates an alternative structure where the horn 128 is intended to intermittently contact the active conductor run to achieve a stitch type adherence in a single operation. Fig. 13 illustrates another alternative where a narrow ultrasonic horn 129 movable relative to the longitudinal axis of the mandrel is used to achieve a similar intermittent adherence of the insulated wire. In this case, the horn is moved longitudinally to a desired adherence point and then downward to activate the adhesive. Normally, the active conductor run would be adhered at the ends and at several points there between.

A preferred technique for forming a multi-phase winding, such as a three-phase winding, uses multiple spools of insulated wire. The system first forms the first layer of the first coil of the first phase of the mandrel surface. Next, the first layer of the second coil in the second phase is formed using a different spool of wire. Then, using a third spool of wire, the first layer of the third coil in the third phase is formed. When the first layers of each of the phases have been formed in the mandrel surface, the system again uses the first spool to form the second layer of the first coil in the first phase. The second and third spools are subsequently used to form the second layer in the second and third phases. The winding proceeds in this fashion until the three-phase, multilayer winding is completed. The system is computer controlled so that virtually any desired type winding can be produced. The computer controls not only the rotary position of the mandrel, but also the guide pin positioning and the operating conditions for the ultrasonic horn and its movement. The system is capable of forming windings with as little as a two conductor pole span.

Alternative apparatus for making a three phase winding could include three complete winding stations displaced from one another by 120 degrees.

Fig. 14 illustrates the stator of a linear motor which can be made using the invention. The stator winding structure can be formed on a suitable flat forming surface 130 or, preferably, on the surface that provides the back iron for the stator. If a self-supporting stator winding is first formed and then transferred to the back iron stator structure, the forming surface is preferably coated with a material like Teflon or covered with a film material like Kapton.

The winding structure can be of any suitable configuration for the desired linear motor and is preferably formed using adhesive coated insulated wire. The winding shown in Fig. 14 is a single layered winding where the coils 134, 135, 136 are deposited in a shingle fashion. Although shown as a single layer winding for ease of illustration, the practical winding would normally be multilayered. The wire can be deposited and adhered to the forming surface or previously deposited wire using a scribing head similar to that shown in Fig. 4. The scribing head is designed for controlled movement in the X and Y coordinates. In addition to the adhesive coating on the wire, or as an alternative thereto, an adhesive layer can be placed in the forming surface or between conductor layers. The active conductor portions of the winding are perpendicular to the direction of movement and are parallel to one another.

After the stator winding is formed, it is rigidly adhered to the stator back iron 130. This can be accomplished by curing a two-stage adhesive or by using or adding a thermosetting encapsulant.

As illustrated in Fig. 15, the linear motor includes a moving permanent magnet 140 mounted on a carriage (not shown) for linear movement relative to the stator winding 132. Soft iron pole pieces 142 and 144 are dimensioned so that the distance between the pole faces corresponds to the coil span of the stator winding. The back iron 130 completes the magnetic path for the moving magnet. The coils 134-136 are connected to a suitable switching array designed to energize the coils in succession to achieve the desired linear motion.

The method for forming a motor winding structure according to preferred embodiments of the invention includes the following steps:

(a) Depositing insulated wire on a mandrel or cylindrical support according to a desired winding pattern. Either the support surface, the insulated wire, or both, are covered with a heat activatable adhesive. Further adhesive may be added between conductor layers. The coils of the winding pattern include active segments to be located in the air gap and end turn segments between successive active segments. The active segments are preferably straight and parallel to the axis.

(b) Energy, preferably ultrasonic, is applied while at least part of the insulated wire is being deposited so that the active segments are adhered parallel to the axis of rotation. Alternate energy sources include infrared and laser energy. The winding structure with the adhered portions is semi-rigid and self-supporting.

(c) The self-supporting winding structure is removed from the mandrel and placed inside the

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back iron cylinder of the stator of the motor. The winding is then encapsulated to rigidly secure the winding to the back iron cylinder. Although a separate encapsulating resin can be used, preferably the heat activatable adhesive also includes a thermosetting resin which can be cured to perform the encapsulating function. A preferred alternative is to use an encapsulant in addition to a heat activatable adhesive including a thermosetting resin.

(d) Once the winding structure is in place, the motor assembly can be completed preferably including rotating high energy permanent magnets.

(e) In the case of a linear motor, the insulated wire is deposited on a flat forming surface which can be the back iron of the stator. The active segments of the winding are preferably parallel and perpendicular to the direction of movement. The winding structure, after formation, is encapsulated to rigidly secure the winding to the back irons.

(f) The adhesive can be activated on an ongoing, continuous basis as wire is dispensed or can be activated one segment at a time. The insulated wire can be adhered by activating the adhesive only for active segments of the winding or portions thereof. The insulated wire can also be adhered in an intermittent stitching fashion.

(g) To facilitate removal of the self-supporting winding structure, the mandrel or forming surface can be wrapped with a film material such as Mylar or coated with a material like Teflon.

(h) To facilitate insertion of the self-supporting winding structure into the back iron cylinder (or stator shell), the end turn segments at one end can be displaced inwardly to that the diameter of the end turn segment portion of the winding structure does not exceed the diameter of the active segment portion. The winding structure can then be inserted with the inwardly displaced end turns first. The inward displacement of the end turns can also be achieved by applying heat and pressure sufficient to reactivate the adhesive and inwardly displace the end turns after completion of the winding structure and before insertion into the stator shell.

(i) When the semi-rigid winding structure is placed in the back iron shell, the winding can be outwardly compressed against the shell to increase the conductor packing density and reduce the void space otherwise filled with encapsulant. The outward compression can be achieved using an inflatable balloon, an expandable split roller, a drawing operation, or other known techniques. Heat can also be applied so that the compression and heat temporarily con-

vert the adhesive to the plastic state. Alternately, the compression step can be carried out while the winding structure is inserted in a fixture prior to being placed in the back iron shell.

(j) The adhesive and/or encapsulant can comprise a resin composition in which the filler normally present in the composition is replaced by powdered particles of magnetically soft material such as iron or Metglass. Preferably, the particles are precoated with an electrically insulating layer. The particles are used to improve the magnetic and thermal properties of the motor. The filler can also be replaced by ceramic particles, industrial diamond chips or other materials with high thermal conductivity.

(k) As an alternative to using a back iron cylindrical shell, the winding structure can be wrapped with adhesive coated soft iron wire. Normally, five or six layers of iron wire are sufficient. The wire wrap provides the back iron with minimum spacing between the winding and the back iron to minimize the encapsulant and consequent thermal barrier. A further advantage of using a wrapped iron wire shell is that it facilitates complex multi-winding structures including winding used for rotor position sensing or for field weakening motor control.

(l) Instead of a mandrel, the actual rotor of the motor could be used. The rotor is wrapped with one or more layers of a film material like Mylar to provide a working space between the rotor and stator. In a preferred embodiment, care is taken to provide a uniform surface for formation of the winding. The winding structure is formed on the Mylar as is the case when using a mandrel.

## Claims

1. A method for the manufacture of a slotless stator for an electromechanical transducer including a pre-formed, at least partially rigid, self-supporting winding structure having active segments and end-turn segments, said method comprising the steps of depositing insulated wire on a support surface; adhesively affixing at least active wire segment portions of said insulated wire to said support surface or previously deposited wires, with at least active wire segments of said winding structure attached in predetermined, substantially fixed positions with respect to other active segments of said winding structure; encapsulating and securely attaching said winding structure to the metal structure of the slotless stator; and combining the completed stator with one or more permanent magnet structures mounted for movement relative to said stator.

- 2. The method of claim 1 wherein the winding structure is removed from said support surface and inserted in the slotless stator structure or shell.
- 5 3. The method of claim 1 or 2 wherein said active segments are arranged substantially parallel to each other.
- 10 4. The method of claim 1 wherein the support surface, or the wire, or both, is (are) provided with an adhesive layer that is activated substantially simultaneously with, or subsequent to, the application of each conductor segment of the winding structure.
- 15 5. The method of claim 1 or 2 wherein the electromechanical transducer is a rotary motor and wherein said active segments are arranged substantially parallel to the axis of rotation.
- 20 6. The method of claim 1 or 2 wherein the electromechanical transducer is a linear motor and wherein said active segments are arranged substantially perpendicular to the direction of movement.
- 25 7. The method of claim 1 wherein at least part of the active segments is adhesively fixed in position prior to depositing subsequent active segments.
- 30 8. The method of claim 1 wherein at least one or more section(s) of active wire segment portions of said insulated wire is (are) adhesively affixed to said support surface or previously deposited wires, with at least one active wire segment, or part of such segment, attached at a time.
- 35 9. The method of claim 8 wherein the adhesive coated wire is activated while depositing said wire by progressively applying sufficient energy at the point of contact for adhering the wire to form winding structure.
- 40 10. The method of claim 8 wherein the adhesive coated wire is activated for an entire segment at one time.
- 45 11. The method of claim 8 wherein the adhesive coated wire is activated intermittently for an active segment.
- 50 12. The method of claim 4 wherein the adhesive layer is activated substantially simultaneously with, or subsequently to, the application of each active conductor segment of the winding

structure.

13. An electromechanical transducer comprising the stator of claim 1 or 2 and one or more permanent magnet structure(s) mounted for movement relative to said stator. 5

14. An electric motor comprising the stator of claim 1 or 2 and a rotor comprising one or more permanent magnet(s). 10

15. An electric motor comprising the stator of claim 1 or 2 and one or more permanent magnet(s) movable linearly relative to said stator. 15

16. A method for the manufacture of a rotating electromechanical transducer including a slotless stator with a pre-formed, at least partially rigid winding structure inside a stator shell and a rotor provided with one or more permanent magnet(s), said method comprising the steps of

(1) placing insulated wire on a cylindrical support surface, either said wire or said surface, or both, being coated or provided with an adhesive layer that can be activated by application of energy; 25

(a) part of said insulated wire being dispensed parallel to the axis of said cylindrical support surface while travelling towards one end of said support surface to form an active conductor segment of said winding structure; 30

(b) part of said insulated wire being dispensed to form a wire loop constituting an end-turn; 35

(c) part of said insulated wire being thereafter dispensed while travelling in the reverse direction parallel to said axis to form another active conductor segment of said winding structure; 40

(d) part of said insulated wire being next dispensed to form another wire loop constituting an end-turn; 45

(e) repeating steps (a) to (d) until all winding coils of said winding structure are completed;

(2) adhesively attaching at least portions of each active conductor segment, a section at a time, before forming the next segment constituting an active part of a winding structure, thereby forming a cylindrical winding structure with at least the active conductor portions being adhered; 50

(3) encapsulating said winding structure and simultaneously adhesively bonding it to the stator shell, using as the encapsulant a resinous composition; 55

(4) completing the assembly of the electromechanical transducer to include at least one rotating permanent magnet rotor structure.

17. A method for the manufacture of a rotating electromechanical transducer including a slotless stator having a metal structure with a pre-formed, at least partially rigid winding structure inside a stator shell and a rotor provided with one or more permanent magnet(s), said method comprising the steps of

(1) dispensing and depositing insulated wire with wire scribing means on a cylindrical support surface, either said insulated wire or said cylindrical surface, or both, being provided with an adhesive layer that can be activated by application of energy;

(a) part of said insulated wire being dispensed parallel to the axis of said cylindrical support surface while travelling towards one end of said support surface to form an active conductor segment of said winding structure;

(b) part of said insulated wire being dispensed to form a wire loop constituting an end-turn;

(c) part of said insulated wire being thereafter dispensed while travelling in the reverse direction parallel to said axis to form another active conductor segment of said winding structure;

(d) part of said insulated wire being next dispensed to form another wire loop constituting an end-turn;

(e) repeating steps (a) to (d) until all winding coils of said winding structure are completed;

(2) substantially simultaneously with dispensing at least part of said insulated wire, adhesively attaching at least portions of each active conductor segment on a continuous basis to form a cylindrical winding structure with at least the active conductor portions being adhered;

(3) encapsulating said winding structure with a resinous composition while simultaneously adhesively bonding said winding structure to the stator shell;

(4) disposing a rotor with at least one permanent magnet within said winding structure and completing the assembly of the electromechanical transducer.

18. The method of claim 1, 16 or 17, further including the step of compressing said winding structure by exerting pressure, or pressure and

heat, sufficient to temporarily convert the adhesive to a plastic state.

19. The method of claim 18 wherein said winding structure is compressed before encapsulating and securely attaching it to the metal structure of the slotless stator. 5

20. The method of claim 18 wherein the step of compressing is carried out with the step of encapsulating. 10

21. The method of claim 16 or 17 wherein said end-turns, at least at one end of said winding structure, are displaced in a direction perpendicular to the axis of the cylindrical support. 15

22. The method of claim 21 wherein said winding structure is inserted in a slotless stator shell with the inwardly displaced end-turns first. 20

23. The method of claim 16 or 17 further outwardly compressing the winding structure by inserting an expandable means therein and exerting outwardly directed pressure, or pressure and heat, for temporarily converting the adhesive to its activated plastic state. 25

24. The method of claim 1 or 16 wherein the insulated wire is adhesive coated and located between guides relative to said cylindrical support surface to form active conductor segments extending substantially parallel to the axis of said cylindrical support, further comprising applying tension to the insulated wire between said guides, and affixing at least a portion of the active segments to the said support surface, or the surface of a previously formed conductor layer, after tension has been applied. 30

25. The method of claim 1, 16 or 17 wherein the winding structure is arranged in a plurality of conductor layers. 45

26. The method of claim 1 or 25 wherein adhesive is applied to a deposited wire prior to depositing the next winding layer. 50

27. The method of claim 1, 16 or 17 wherein the adhesive is activated by the application of ultrasonic, infrared, heat or laser energy. 55

28. The method of claim 1, 16 or 17 wherein the adhesive, in its non-activated state, is solid and non-tacky, can be activated to its active, tacky and plastic state by application of energy of a certain level, and reverts to its solid, non-tacky state when energy is no longer applied.

29. The method of claim 28 wherein the adhesive may be activated to its tacky state by application of energy at one level and, in a later step, may be fully cured to its thermoset state by application of energy at a higher level. 60

30. The method of claim 1, 16 or 17 wherein the encapsulant for encapsulating the winding structure, and the adhesive are substantially completely cured simultaneously. 65

31. The method of claim 1, 16 or 17 wherein the end-turns are reformed by application of pressure or heat, or both, bring said end-turn closer to, or in mechanical contact with, the stator shell surface. 70

32. The method of claim 1, 16 or 17 wherein the encapsulant comprises a filler with high thermal conductivity. 75

33. The method of claim 32 wherein part or all of the filler consists of finely divided particles of magnetically soft material. 80

34. The method of claim 33 wherein the magnetically soft material is Met-glass(R). 85

35. The method of claim 33 wherein the particles are pre-coated with an electrically insulating layer. 90

36. The method of claim 1, 16 or 17 wherein part or all of the magnetic stator structure is formed and attached to the outer surface of said winding structure by injection molding using a resin composition filled with finely divided particles of magnetically soft material. 95

37. The method of claim 1, 16 or 17 wherein soft magnetic material wire is applied to the outer surface of the formed winding structure to form the magnetic stator structure surrounding the winding, the method comprising the steps of (a) arranging adhesive coated wire of soft magnetic material in a plurality of layers surrounding said winding structure; (b) adhesively bonding said magnetic material wire to said outer surface of said winding structure and each other; (c) consolidating the resulting structure by applying energy and pressure. 100

38. The winding structure made by the method of claims 1, 16 or 17. 105

39. The slotless stator made by the method of claims 1, 16 or 17.

40. The electromechanical transducer made by the method of claims 1, 16 or 17. 5

41. Apparatus for manufacturing self-supporting winding structures for slotless stators including a magnetic stator shell comprising  
a cylindrical carrier mandrel providing a cylindrical support surface;  
a drive for controlling the rotary position of said mandrel;  
means for dispensing insulated wire with an adhesive coating that can be activated to a plastic adhesive state by the application of energy;  
a drive for moving said dispensing means to arrange insulated wire parallel to the axis of said cylindrical mandrel to form active conductor segments of the winding structure and to dispense wire to form end-turns between said active conductor segments;  
means for activating said adhesive coating to said plastic adhesive state to adhere at least part of said active conductor segments, a section at a time, to form a self-supporting winding structure; and  
means for inserting said self-supporting winding structure into said stator shell and securing said winding structure therein. 10

42. Apparatus according to claim 41 further comprising guide pins in the area of said mandrel to define the end-points for active conductor segments. 15

43. Apparatus according to claim 42 wherein said guide pins are retractable. 20

44. Apparatus for manufacturing self-supporting winding structures for slotless stators including a magnetic stator shell comprising  
a cylindrical carrier mandrel providing a cylindrical support surface;  
a drive for controlling the rotary position of said mandrel;  
means for dispensing insulated wire with an adhesive coating that can be activated to a plastic adhesive state by the application of energy;  
a drive for moving said dispensing means to deposit insulated wire parallel to the axis of said cylindrical mandrel to form active conductor segments of the winding structure and to dispense wire to form end-turns between said active conductor segments;  
means for activating said adhesive coating 25

to said plastic adhesive state on a continuous basis as wire is dispensed to adhere at least part of said active conductor segments to form a self-supporting winding structure. 30

45. Apparatus according to claim 42 or 44 wherein said mandrel has reduced diameter areas corresponding to the end-turn portions of the winding structure formed on said support surface. 35

46. Apparatus according to claim 42 or 44 including means for dispensing insulated wire capable of dispensing a plurality of wires at the same time. 40

47. Apparatus according to claim 42 or 44 including a plurality of means for simultaneously dispensing insulated at different radial positions on said cylindrical support. 45

48. An encapsulant for encapsulating and securely attaching a stator winding structure in a stator shell comprising a resin composition wherein at least part of the filler present in said composition consists of powdered particles of magnetically soft material. 50

55

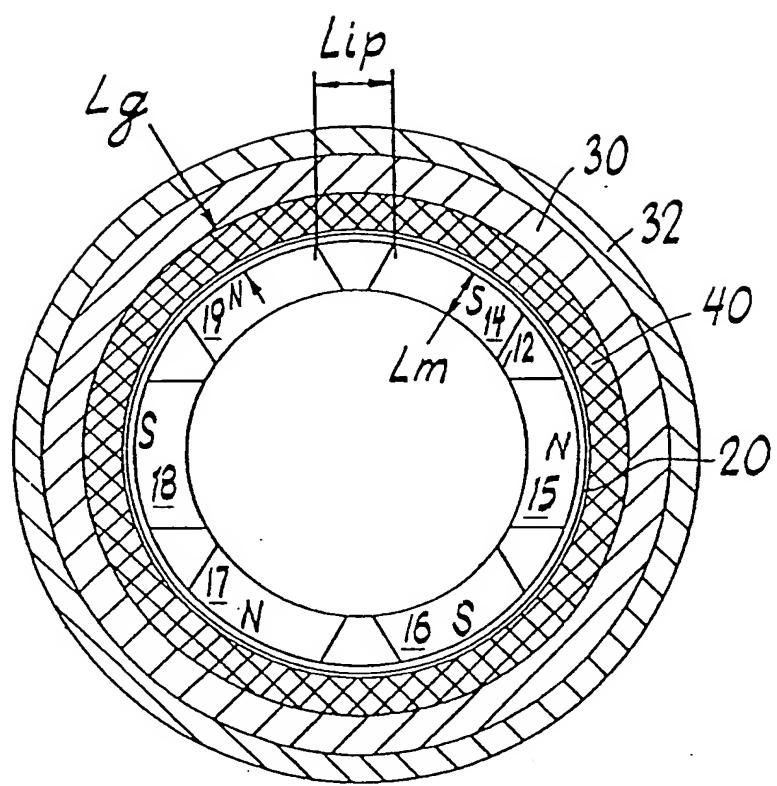


FIG. 1

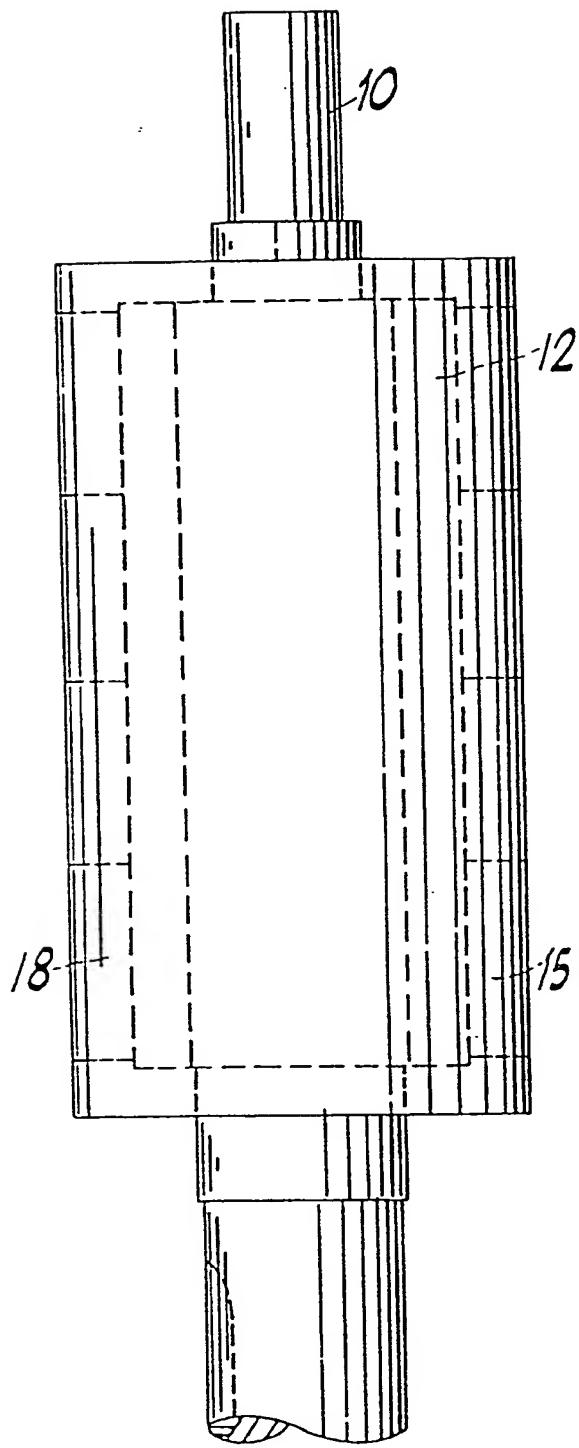


FIG. 2 A

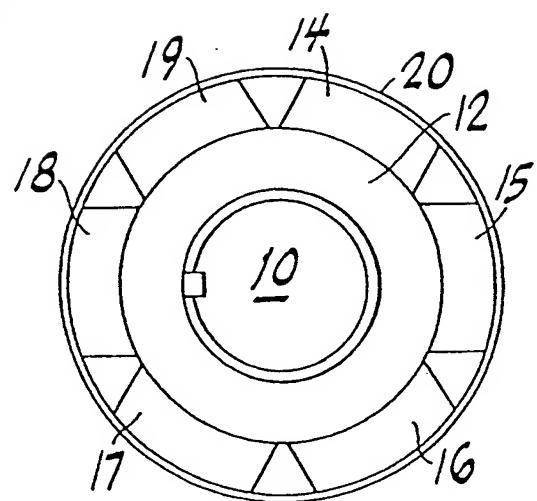


FIG. 2 B

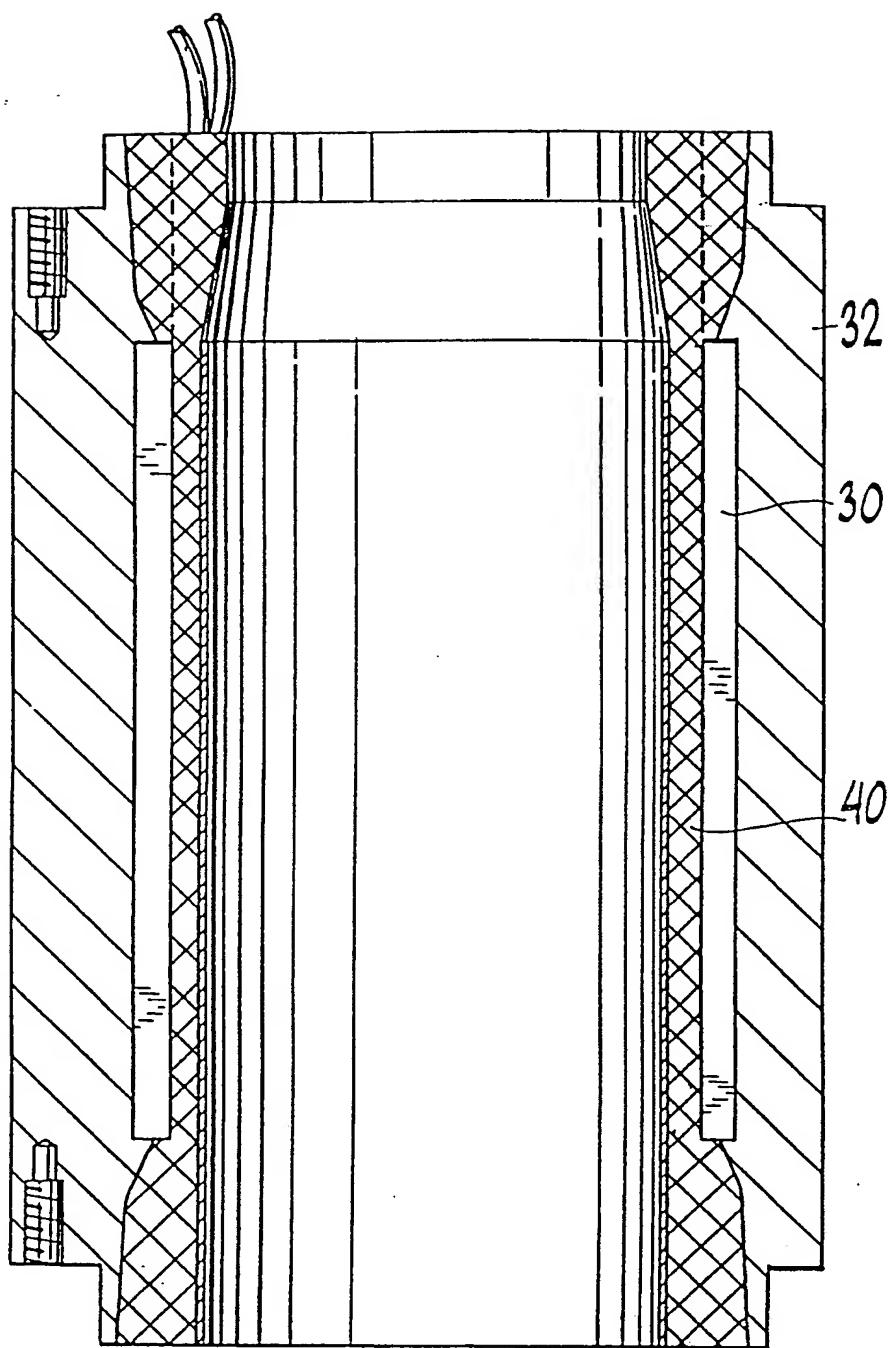


FIG. 3

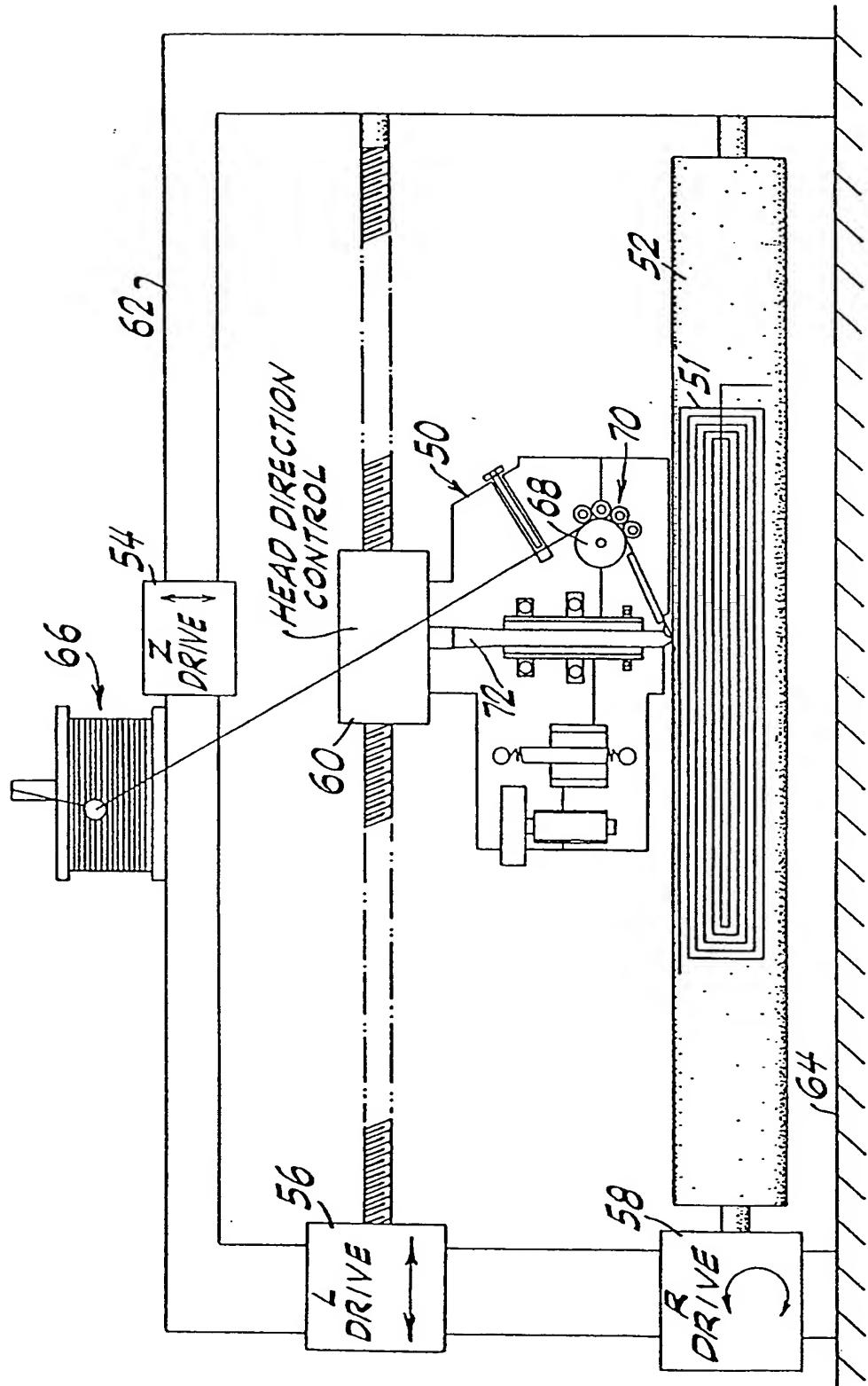


FIG. 4

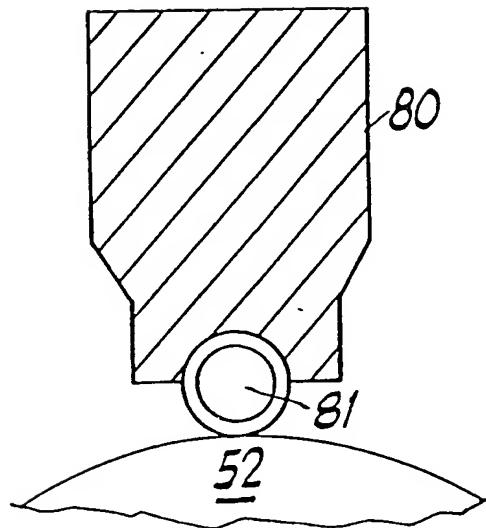


FIG. 5A

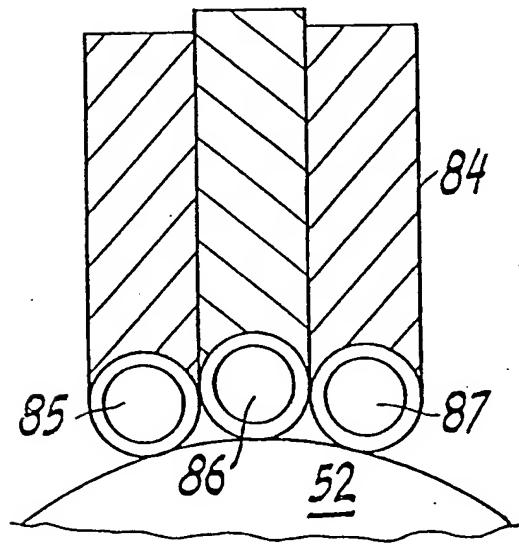


FIG. 5B

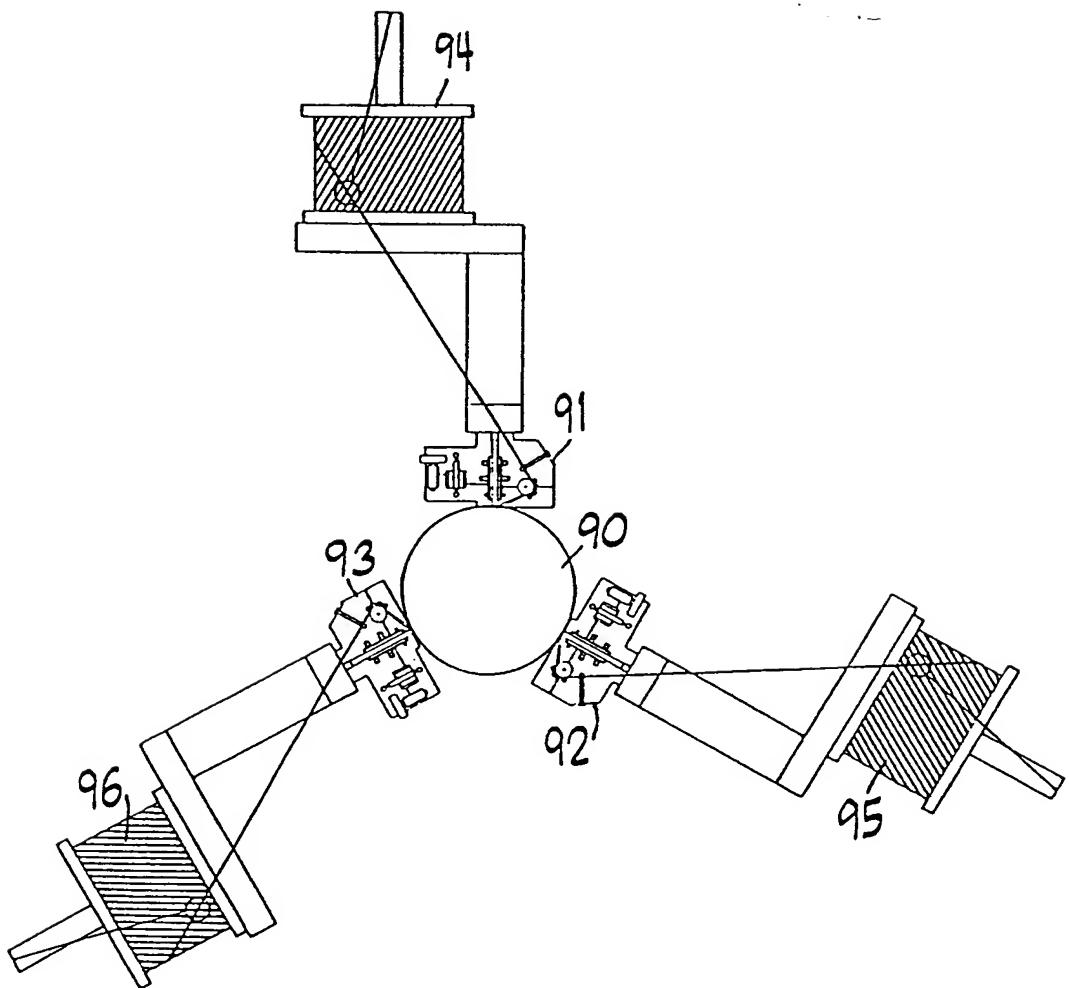


FIG. 6

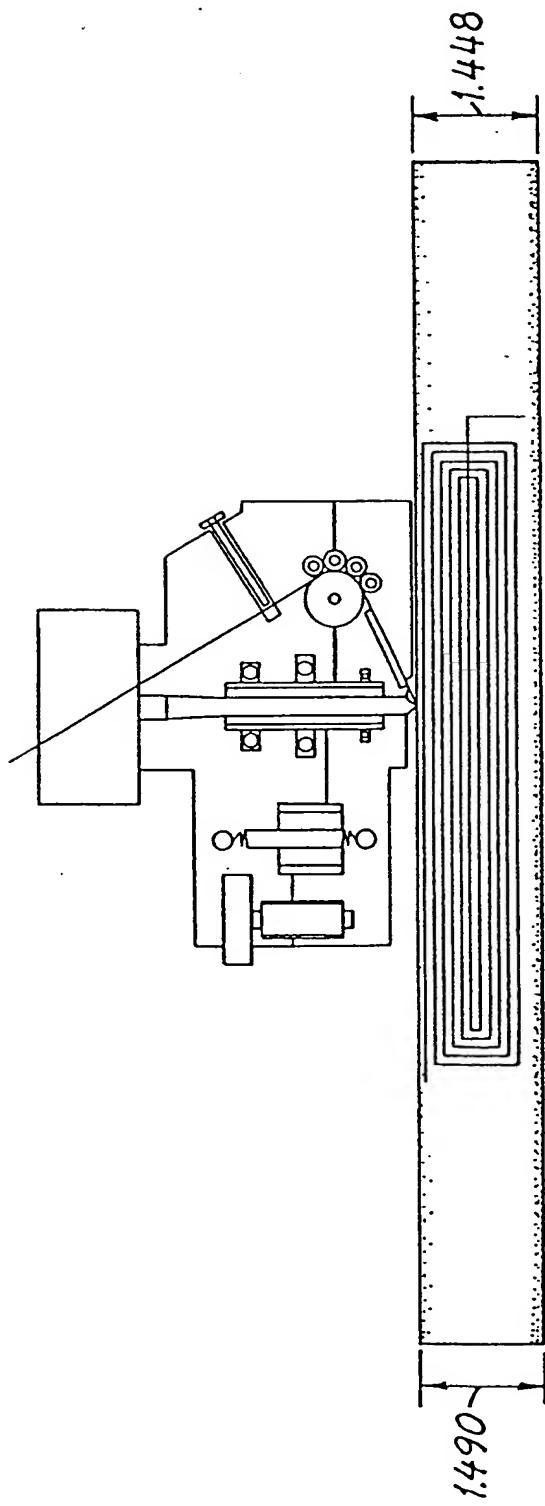


FIG. 7

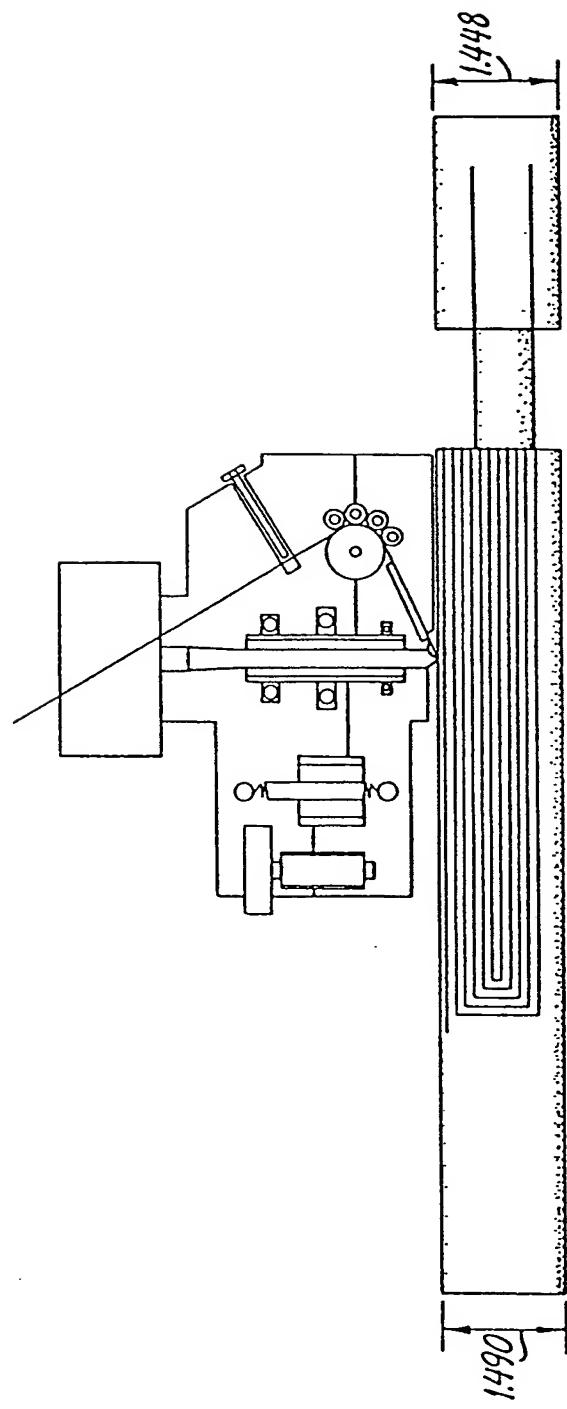
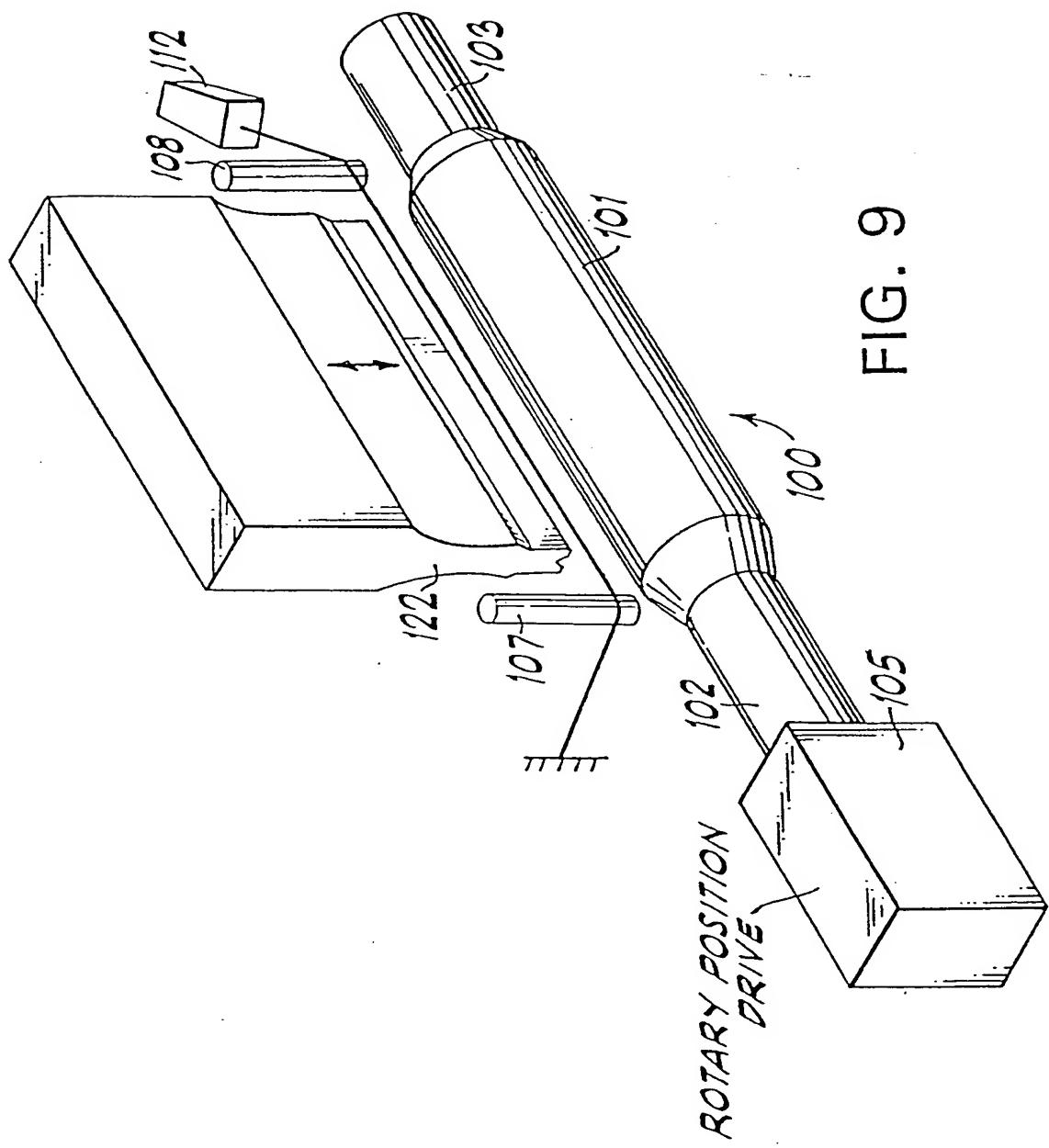


FIG. 8



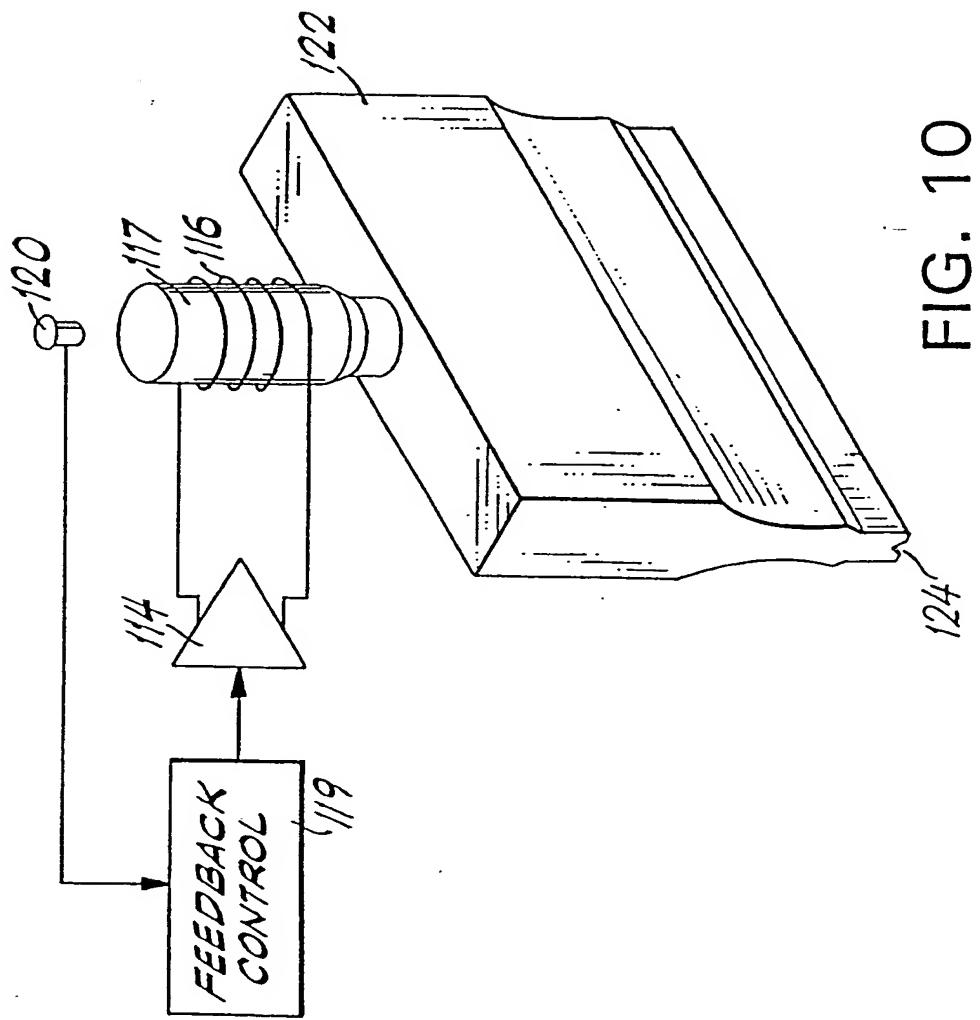


FIG. 10

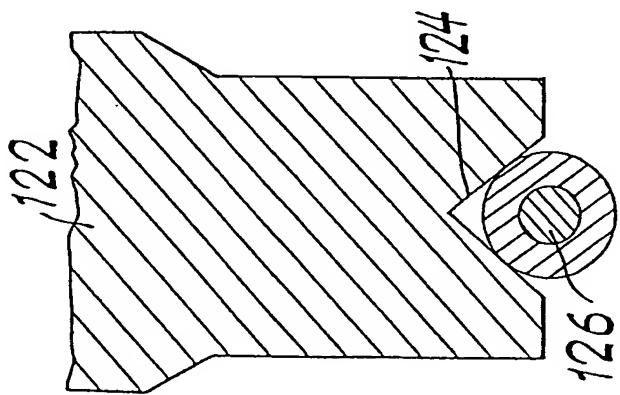


FIG. 11

FIG. 12

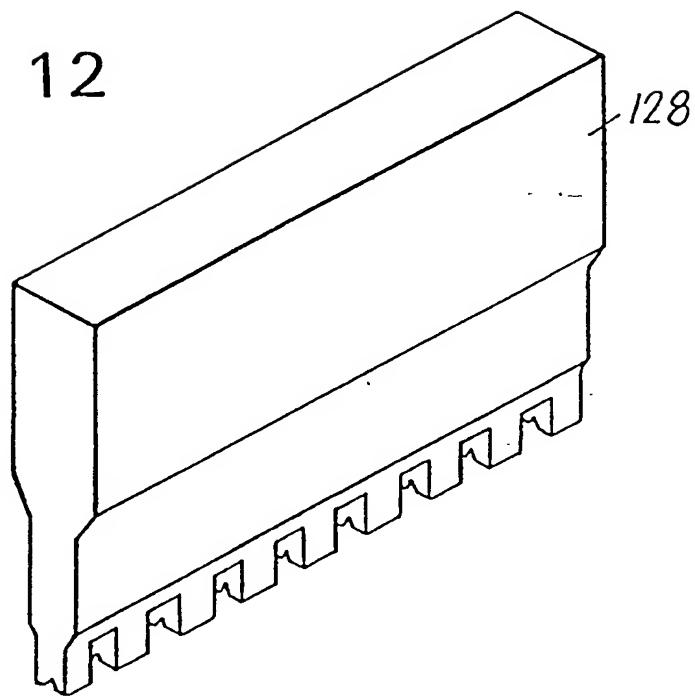


FIG. 13

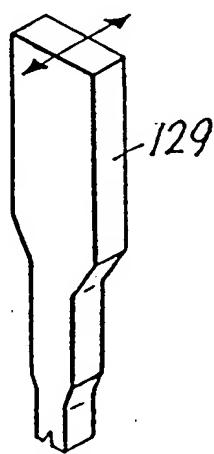


FIG. 14

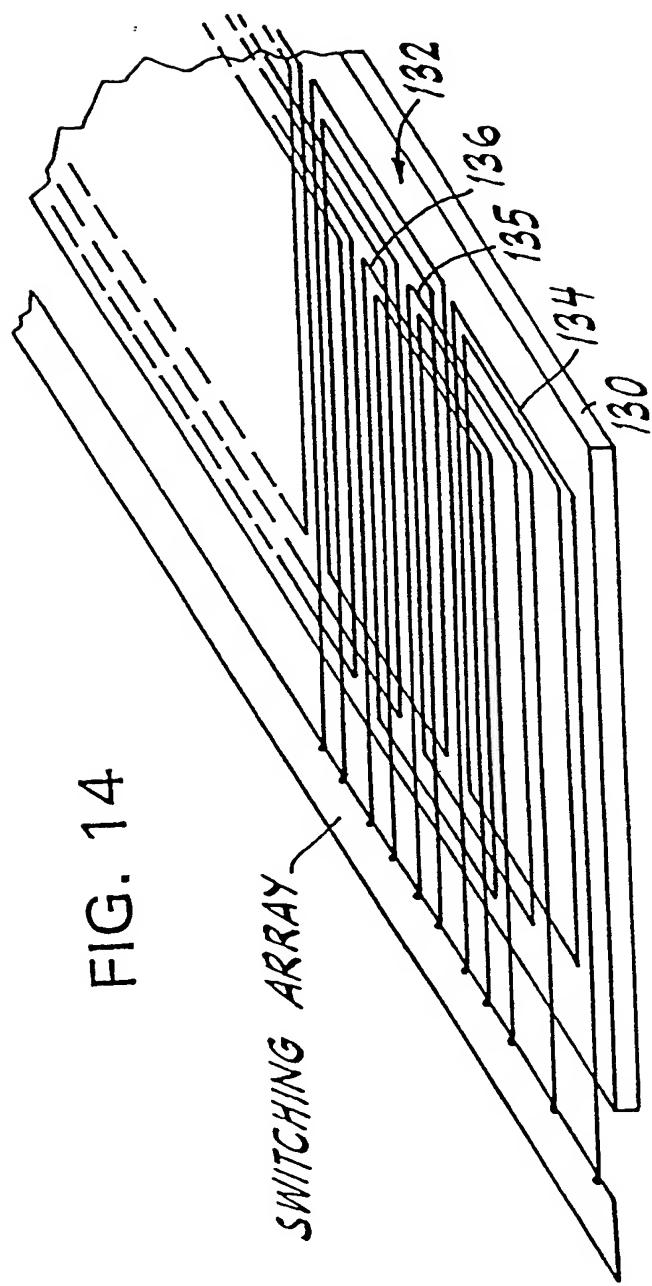


FIG. 15

